

# Cosmic Rays and the Monogem Supernova Remnant

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## Abstract

Recent findings indicate that the Monogem Ring and the associated pulsar PSR B0656+14 may be the ‘Single Source’ responsible for the formation of the sharp knee in the cosmic ray energy spectrum at  $\sim$ 3PeV. The energy spectrum of cosmic rays expected for the Monogem Ring supernova remnant ( SNR ) from our SNR acceleration model [1] has been published by us elsewhere [2]. In this paper we go on to estimate the contribution of the pulsar B0656+14 to the cosmic rays in the PeV region. We conclude that although the pulsar can contribute to the formation of the knee, it cannot be the dominant source of it and an SNR is still needed.

We also examine the possibility of the pulsar giving the peak of the extensive air shower ( EAS ) intensity observed from the region inside the Monogem Ring [3]. The estimates of the gamma-ray flux produced by cosmic ray particles from this pulsar indicate that it can be the source of the observed peak, if the particles were confined within the SNR during a considerable fraction of its total age. The flux of gamma quanta at PeV energies has a high sensitivity to the duration of the confinement. The estimates of this time and of the following diffusion of cosmic rays from the confinement volume turn out to be in remarkable agreement with the time needed for these cosmic rays to propagate to the solar system and to form the observed knee in the cosmic ray energy spectrum.

Other possible mechanisms for the production of particles which could give rise to the observed narrow peak in the EAS intensity were also examined. Electrons scattered on the microwave background or on X-rays, emitted by SNR, can not be responsible for the gamma-quanta in the peak. Neutrons produced in PP - collisions or released from the disintegration of accelerated nuclei seem to be also unable to create the peak since they cannot give the observed flux.

If the experimental EAS results concerning a point-like source are confirmed, they can be important, since

- (i) they will give evidence for the acceleration of protons or heavier nuclei by the pulsar;
- (ii) they will give evidence for the existence of a confinement mechanism in SNR ;
- (iii) they will confirm that cosmic rays produced by the Monogem Ring SNR

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and associated pulsar B0656+14 were released recently giving rise to the formation of the sharp knee and the observed narrow peak in the EAS intensity ; (iv) they will give strong support for the Monogem Ring SNR and the associated pulsar B0656+14 being identified as the Single Source proposed in our Single Source Model of the knee.

A number of predictions of the examined mechanism are made.

## 1 Introduction

A few years ago we suggested the ‘Single Source Model’ to explain the remarkable sharpness of the knee in the cosmic ray energy spectrum at  $\sim 3$  PeV [4, 5], a feature noticed even in the first publication on this subject, 46 years ago [6]. The model is based on the assumption that a single, relatively recent and nearby supernova remnant contributes significantly to the cosmic ray intensity at PeV energies. The sharpness is due to the cutoff in the energy spectrum of cosmic rays accelerated by SNR. According to the theoretical model of the SNR acceleration mechanism developed by Berezhko et al. [7] the cutoff for the acceleration in the hot and low density interstellar medium (ISM) is at a rigidity of  $\sim 0.4$  PV. To match the position of the knee at an energy of  $\sim 3$  PeV and to explain the second peak of the intensity at  $\sim 10\text{-}15$  PeV, observed in most of the experiments, the model assumes that the Single Source emits predominantly medium (oxygen) and heavy (iron) nuclei with an admixture of sub-iron nuclei. This assumption is reasonable, in view of the ISM, which provides the nuclei, having been seeded by a previous supernova (see the next paragraph). Comparing the shape of the energy spectrum of cosmic rays from the Single Source and its total energy content with the model of SNR acceleration and the propagation of cosmic rays through the ISM we derived a likely interval of distance (230-350 pc) and age (84-100 kyear) for the Single Source [30].

On the basis of our estimates of distance and age we calculated the possible flux of high energy gamma rays from the Single Source and found that it is unlikely to be observed at sub-GeV and TeV gamma rays with gamma telescopes of the present sensitivity [2]. The reason is that being nearby the Single Source is in our Local Superbubble with its low ( $\sim 3 \cdot 10^{-3} \text{ cm}^{-3}$ ) density of target gas and the SNR should not be a discrete source, but extended with an angular radius of  $\sim 20^\circ$ . It is difficult to detect an excess intensity from such an extended source since the estimates of the background are very unreliable. Among the sources which would satisfy these limits of distance and age we indicated the Monogem Ring and Loop I [8]. The same sources were also discussed in connection with their possible contribution to the flux of high energy electrons [9, 10, 11].

Recently, Thorsett et al. [12], using the triangulation technique found the distance of the pulsar PSR 0656+14 associated with the SNR Monogem Ring. It is  $288 \pm 30$  pc and its spin-down age is  $\sim 110$  kyears, both of which are in remarkable agreement with our estimates for the Single Source [2]. Such determinations had not previously been possible from observations of the SNR itself. Thorsett et al.

themselves claimed that the SNR Monogem Ring and its associated pulsar PSR 0656+14 can be the Single Source responsible for the formation of the knee.

Armenian physicists have studied the sky near the Monogem Ring in the sub-PeV and PeV range using the EAS technique and found a  $6\sigma$  excess of the EAS intensity in one of their angular bins [3]; we refer to this interesting result as the ‘Armenian peak’. Since their bin of  $3^\circ \times 3^\circ$  is narrower than the size of the SNR it is thought that the excess is not due to the extended source, but to a discrete source, viz. the pulsar.

Bhadra [13] analysed theoretically the possibility for a pulsar to be the Single Source, and concluded that the most likely pulsar candidates are Geminga and Vela.

In this paper we analyse the possibility of the pulsar PSR B0656+14, associated with the SNR Monogem Ring, being the Single Source responsible for the knee and also see to what extent the ‘Armenian peak’ could come from the same object. Independently, we search for other evidence which might confirm the reasonableness of the peak.

## 2 Calculation of the pulsar energy spectrum

At the beginning we consider the pulsar as an isolated neutron star. The difference between the temporal dependence of particle acceleration by such a pulsar and by the SNR is that in the former case the process is continuous from the very beginning. At any time instant three processes follow, sequentially: emission of accelerated particles by the pulsar, propagation through the ISM and leakage from the Galaxy. On the contrary the acceleration by the expanding SNR shock wave is most likely not accompanied by immediate particle emission, rather, due to the compression of magnetic fields, the particles are confined within the shell for some time after the SN explosion and then released to ‘outer space’ followed by diffusion and eventual escape from the Galaxy. For an isolated pulsar, however, we postulate that the other radiations, associated with it, so perturb the ambient magnetic field that the very energetic particles have easy, and prompt egress.

The energy spectrum of emitted particles for an isolated pulsar was considered as being equal to a mean spectrum emitted by a number of pulsars and averaged over an isotropic distribution of  $\theta$ , where  $\theta$  is an angle between the spin axis and magnetic dipole axis of the pulsar. The spectrum has been deduced on the basis of works [14, 15, 16] in the framework of the following scenario. If the emitted particles are beamed along the magnetic dipole axis, then their total number will be proportional to the solid angle as  $\frac{dN}{d\theta} \propto \sin\theta$ . An energy spectrum of accelerated particles is connected with  $\frac{dN}{d\theta}$  as  $\frac{dN}{dE} = \frac{dN}{d\theta} / \frac{dE}{d\theta}$ . If the particle energy  $E$  changes with  $\theta$  as  $E = E_{max} \sin\theta$  then  $\frac{dE}{d\theta} = E_{max} \cos\theta$  and  $\frac{dN}{dE} \propto \tan\theta = \frac{E/E_{max}}{\sqrt{1-(E/E_{max})^2}}$ . We applied this averaged spectrum for the case of an individual pulsar, because of the lack of knowledge of the particular value of  $\theta$ .

We adopted the total energy contained in this spectrum as being equal to  $E_{max}$ .

The further normalization to the total rotation energy loss  $\dot{E}_{rot}$  results in the particle emission rate as a function of their energy and time being given by:

$$\frac{d^2N}{dEdt} = \frac{4\dot{E}_{rot}E}{\pi E_{max}^3 \sqrt{1 - (E/E_{max})^2}} \quad (1)$$

Here  $E$  is the particle energy,  $t$  is the time since the creation of the pulsar,  $E_{max}$  is the maximum energy of the emitted particles, which is equal to

$$E_{max} = \frac{E_{max}^0}{1 + 2t/T_0} \quad (2)$$

where  $E_{max}^0 (GeV) = 3 \cdot 10^{-7} Z \sqrt{\frac{3I\dot{P}_0}{2cP_0^3}}$  is the maximum energy at  $t = 0$ ,  $Z$  is the particle charge,  $I$  - the pulsar moment of inertia, taken as  $10^{45}$  gcm<sup>2</sup>,  $P_0$ , sec and  $\dot{P}_0$  - the initial period of rotation and its time derivative respectively,  $c$  - the speed of light and  $T_0 = P_0/\dot{P}_0$ .  $\dot{E}_{rot}$  is the rate of the rotation energy loss, which is equal to

$$\dot{E}_{rot} = \frac{\dot{E}_0}{(1 + 2t/T_0)^2} \quad (3)$$

where  $\dot{E}_0$  is the rate of energy loss at the initial time,  $t = 0$ . Here we assume that all the rotational energy lost by the pulsar is given to cosmic ray particles; this is certainly an extreme assumption, but it gives an upper limit for our estimates of the cosmic ray intensity.

There is a minor difference between our consideration and that of the authors of [14, 15, 16]. They assumed that at any instant the pulsar emits monoenergetic particles, i.e. their spectrum looks like a line at the energy  $E_{max}$ . Inspite of this difference, our expression (1), with its evident divergence in the denominator, which follows from the mathematical treatment of the adopted assumptions and not necessarily is realized in nature, when integrated over the pulsar lifetime gives the same well known spectrum  $\frac{dN}{dE} \sim E^{-1}$ , as in the case of monoenergetic particles.

The propagation model includes both diffusion and escape from the Galaxy. Such a combination is used, because though the diffusion has been considered in the non-uniform ISM this non-uniformity did not include effects connected with the finite dimensions of the Galactic disk and the ensuing escape of particles from the process of diffusion and from the Galaxy.

The survival against leakage from the Galaxy is described by the usual expression, taken from the leaky box model:

$$S(t, T, E) = \exp\left(-\frac{T-t}{\tau(E)}\right) \quad (4)$$

where  $T$  is the spin-down age of the pulsar,  $\tau(E)$  is the mean life time of particles in the Galaxy, which depends on the particle energy  $E$  and charge  $Z$  as  $\tau(E)$ , year =

$\tau_0(E/Z)^{-\delta}$ , with  $E$  - in GeV,  $\tau_0 = 4 \cdot 10^7$  year and  $\delta = 0.5$  in our part of the Galaxy [18].

The diffusion of cosmic rays from the pulsar to the solar system is described by ‘anomalous diffusion’ in the fractal-like ISM with the index  $\alpha = 1$  [19, 20, 2]. The density of cosmic ray particles at a distance  $R$  from the source, emitted and observed at the time  $t$  and  $T$  respectively, is described for the case of spherical diffusion by

$$\rho(t, T, R, E) = \frac{1}{\pi^2 R_d^3 (1 + (R/R_d)^2)^2} \quad (5)$$

Here  $R_d(E) = H_z (\frac{T-t}{\tau(E)})^{\frac{1}{\alpha}}$  is the diffusion radius for our assumed scale height of  $H_z = 1000$  pc. For comparison, we also considered the propagation, described by normal gaussian diffusion, with

$$\rho(t, T, R, E) = \frac{1}{8\pi^{\frac{3}{2}} R_d^3} \exp(-(R/2R_d)^2) \quad (6)$$

and  $\alpha = 2$  [19].

The energy spectrum of cosmic rays is calculated as

$$\frac{dN}{dE} = \int_0^T \frac{c}{4\pi} \frac{d^2N}{dtdE} S(t, T, E) \rho(t, T, E, R) dt \quad (7)$$

The observed parameters of the pulsar PSR 0656+14 are  $P_0 = 0.3848$  s,  $\dot{P} = 5.5032 \cdot 10^{-14}$  [22]. We took the age of this pulsar as  $T = 1.005 \cdot 10^5$  year, a value of 10 years for the  $T_0$  parameter and  $R = 288$  pc for the distance [12]. The calculations show that the spectrum does not depend on the initial conditions for a wide interval of  $T_0 : 1 - 100$  years. For these numerical values of the parameters,  $E_{max}^0 = 4.83 \cdot 10^9$  GeV,  $\dot{E}_0 = 4.08 \cdot 10^{53}$  GeV year $^{-1}$ . Calculations have been made for the energy spectrum of cosmic ray protons (  $Z = 1$  ) and oxygen nuclei (  $Z = 8$  ), ( assuming that oxygen nuclei could, in fact, be taken from the pulsar surface and accelerated by it ). The result is only weakly dependent on the mode of diffusion. The position of the peak in the energy spectrum is practically the same for both normal and anomalous diffusion. The energy contained in *observed* cosmic rays is, for the case of anomalous diffusion, higher by a factor of 2.5, compared with that for the normal diffusion. The result for anomalous diffusion is shown in Figure 1.

### 3 Contribution of an isolated pulsar to the knee

It is remarkable that the spectrum of cosmic rays has a very sharp peak at a rigidity of 0.25 PV, i.e. a rigidity close to that of the knee. It is the maximum rigidity of the particles emitted by the pulsar at the present time ( neglecting the time for light to travel ). The rapid rise of the spectrum below the peak is due to the shape of the emitted spectrum, which is  $\propto E$  ( up to a maximum ) at any time instant

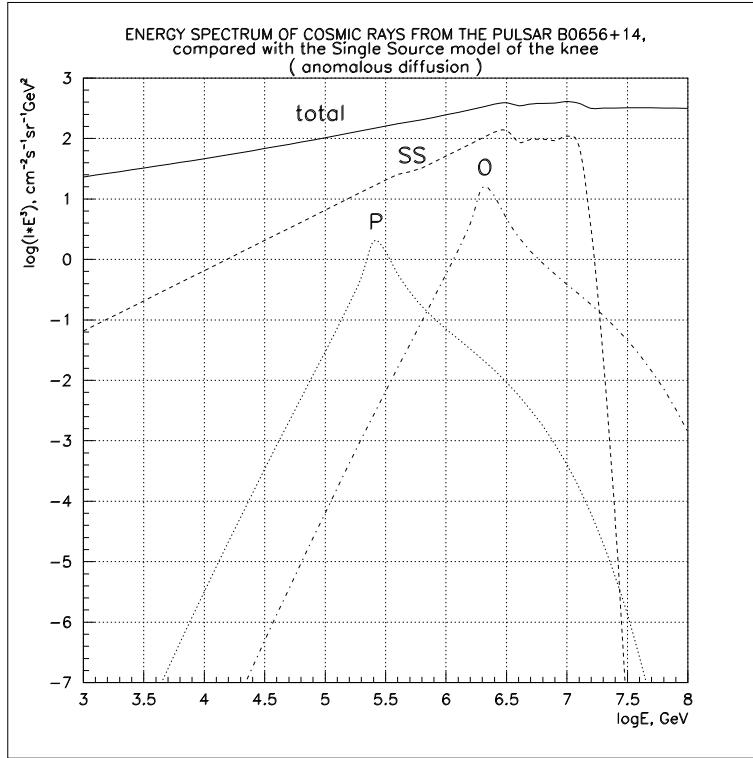


Figure 1: The energy spectrum of cosmic rays from PSR B0656+14 observed at the present time and compared with the Single Source model of the knee [4, 5]: full line - total energy spectrum of cosmic rays; dashed line: energy spectrum of the Single Source, dotted line: energy spectrum of protons accelerated by B0656+14, dash-dotted line - the same spectrum for oxygen nuclei. The knee in the actual spectrum is at  $\log E(\text{GeV}) \approx 6.5$ , close to our pulsar prediction for oxygen.

during the whole life of the pulsar ( see (1) ). The leakage from the Galaxy and the anomalous diffusion through the ISM do not distort this dependence very much.

The steep drop of the spectrum beyond the peak is due to three reasons. The particles of these high energies can be emitted only during a fraction of the pulsar's life time: the higher is the energy - the smaller is that fraction. The escape from the Galaxy is also high and increases with energy. The diffusion of the particles is also very rapid and at the present time almost all the high energy particles have passed the solar system and vanished into space. The diffusive nature of the particle propagation means that the spatial distribution of the particles will be nearly isotropic at the Earth.

The formation of the pulsar spectrum is illustrated in Figure 2, where the particle emission rate, their density after diffusion and the survival probability against escape from the Galaxy are shown at different moments of the pulsar's history.

The energy density contained in the proton and oxygen spectra is the same and equal to  $1.9 \cdot 10^{-6} \text{ eV cm}^{-3}$ . Despite the fact that we normalized the energy transferred to the cosmic rays to the total loss of the rotation energy the cosmic ray

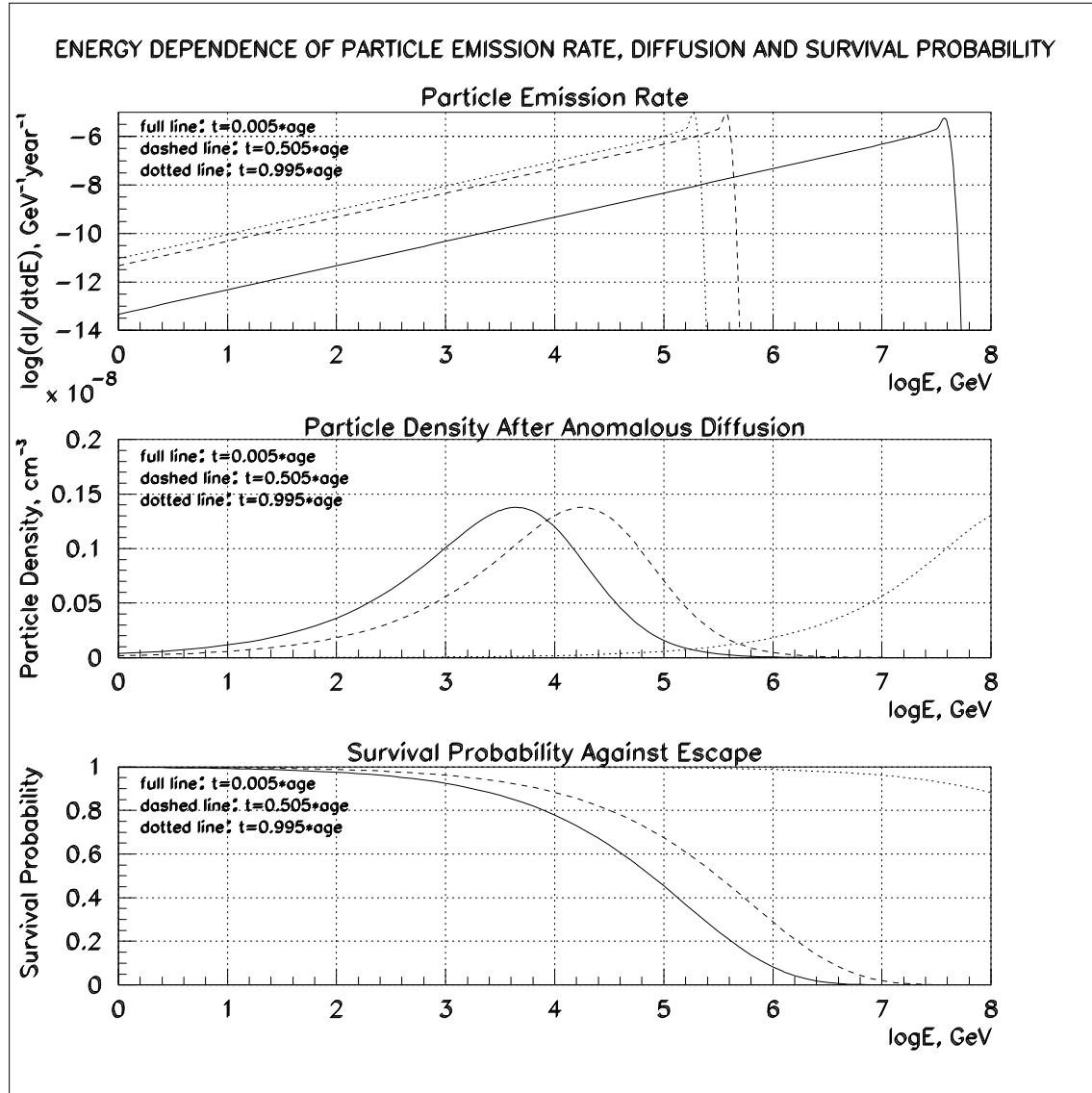


Figure 2: The formation of the energy spectrum of particles from the pulsar at different instants of its history: 0.005 ( full lines ), 0.505 ( dashed lines ) and 0.995 ( dotted lines ) of its age. The upper graph: the particle emission rate, the middle graph: the particle density at Earth after anomalous diffusion and the lower graph: the survival probability against escape from the Galaxy.

energy density turns out to be small compared with the value of  $\sim 2.24 \cdot 10^{-4} eV cm^{-3}$  needed to form the knee in the SS model [2]. If, instead of energy density, we compare the intensity at the knee needed to ensure the observed cosmic ray flux and intensity in the peak for  $Z = 8$ , the difference becomes smaller, but it is still rather large ( $\simeq 7$ ). We conclude, therefore, that the pulsar PSR 0656+14, if it is considered as an isolated neutron star, can contribute up to  $\sim 15\%$  to the formation of the knee, due to the sharpness of its energy spectrum and the closeness of its peak rigidity to the needed value of 0.4 PV, but it seems not to be able to produce enough cosmic rays to be the dominant source of the knee.

## 4 The EAS intensity peak in the Monogem Ring region and the possibility of associating it with the pulsar B0656+14

### 4.1 Observation of the peak

It has been mentioned in the Introduction that since the Monogem Ring SNR is located in our Local Superbubble, with its low gas density, and it is not discrete, but an extended source, which occupies a substantial part of the sky with an angular size of about  $25^\circ$ , we do not expect a measurable flux of high energy gamma quanta from it [2]. However, Armenian physicists looking for regions with an excessive flux of EAS at PeV energies have found such a domain within the Monogem Ring SNR [3] (the ‘Armenian peak’). Their search bin had a size  $3^\circ \times 3^\circ$ , which is not point-like, but definitely smaller than the size of the Monogem Ring SNR itself. The magnitude of the excess was about 6 standard deviations and therefore appears well founded statistically.

The immediate idea, to be examined now, is that inside such an extended source as the Monogem Ring SNR there is an additional discrete source of high energy cosmic rays, which gives this excess. The most plausible discrete source within the SNR is the pulsar, specifically PSR B0656+14. Though the position of the peak is displaced from the present pulsar position, it is reasonable to analyse the probability of this pulsar producing the observable peak. The inevitable diffusive scattering of particles from the SNR and pulsar means that the Armenian peak must be due to gamma rays or neutrons.

An intensity feature of the excess flux is that its spectrum appears somewhat flatter than that of the background flux; such a feature adds to its veracity.

## 4.2 The observed flux and the energy of particles responsible for the peak

Chilingarian et al. [3] do not give an estimate of the observed excessive flux of EAS. However, it is possible to make such an estimate on the basis of their published results. The most reliable peak is established for EAS with a total size  $N_e > 10^6$ . The intensity of such EAS in the vertical direction at the Aragats altitude of 3200 m above sea level, where the MAKET ANI array is operating, is  $(3.3 \pm 0.7) \cdot 10^{-11} \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$  [23, 24]. The mean number of counts per bin in the studied declination band ( $12.5^\circ < \delta < 15.5^\circ$ ) is 18.46. To get this number of counts one needs to have an exposure  $S\Omega T = (5.6 \pm 1.2) \cdot 10^{11} \text{ cm}^2 \cdot s \cdot sr$ . The solid angle for the  $3^\circ \times 3^\circ$  bin is  $2.74 \cdot 10^{-3} \text{ sr}$ , hence  $ST = (2.04 \pm 0.44) \cdot 10^{14} \text{ cm}^2 \text{s}$ . The excess number of counts in the discovered bin was  $25 \pm 6$ , and in order to get this number one needs to have a flux of  $(1.2 \pm 0.4) \cdot 10^{-13} \text{ cm}^{-2} \text{s}^{-1}$ .

If these showers are produced by gamma quanta, their energy for the shower size  $N_e > 10^6$  at 3200 m above sea level should be more than 1.07 PeV [25]. If the showers are produced by neutrons, their energy must be higher and for  $N_e > 10^6$  at Aragats level should exceed 2.5 PeV [26].

## 4.3 Particles from an isolated pulsar

Since the pulsar B0656+14 is at a distance of about 300 pc from the solar system, then if the observed gamma quanta or neutrons are produced by protons from it, they can be born only 900 years ago, i.e. at the present epoch. From the results presented in §2 it is clear that the pulsar B0656+14, if it is an isolated neutron star (i.e. the particles can diffuse freely from it), cannot give particles above its peak energy of 0.25 PeV at the present epoch. Higher energy particles produced in the past would have the necessary higher energy but they have already diffused for a long time and their density in the vicinity of the pulsar at the present epoch is very low. Higher energy particles were also produced in the past, but the majority have already passed beyond the solar system. Heavier nuclei, if they are accelerated by this pulsar, and have higher total energy at the present time, cannot help, since they have even smaller energy per nucleon in the peak of their energy spectrum (Figure 1).

Therefore, if the pulsar B0656+14 is isolated it cannot easily give the Armenian peak at energies above 1 PeV. The word ‘easily’ is used because it is just possible that the effective magnetic field is higher than adopted and with it,  $E_{max}$ . This possibility arises because of the fact pointed out in [27], and used by us in connection with the origin of very energetic particles [28], that the field may have a complicated topography, so that higher multipoles of the field have bigger values than that of the dipole. Nevertheless, the diffusion propagation during the pulsar age has to reduce the cosmic ray density at high energies to such low values that they would not be able to give a measurable effect.

## 4.4 Particles from the pulsar associated with a SNR

There is a way to include into consideration higher energy particles born in the past, but which, however, produce gamma quanta or neutrons at the present time and this is to associate the pulsar with a SNR, since they were both born in the same SN explosion and reject the assumption that the pulsar can be regarded as isolated. In this way we allow the produced particle to be trapped in the SNR in the usual manner for SNR-accelerated particles [1, 11, 21]. The pulsar created as a result of the explosion is located within the shell close to the SNR morphological center. We now assume that cosmic rays accelerated by the pulsar are also confined for the same time as those from the SNR. They are *all* released much later, begin to diffuse from internal regions of the SNR and eventually escape from the Galaxy. Their density in the vicinity of the pulsar is still high. In the process of diffusion through the ISM they produce gamma quanta which can be seen now. This is the scenario.

In fact, the problem of particle escape will be complicated not least because of the effect of the pulsar wind on the ambient ISM in, and near, the ISM. In the original version of the 'Single Source Model' [4, 5], where pulsar-effects are ignored, we assume that the SNR-accelerated particles are *all* trapped until the average cosmic ray energy density is equal to the value outside the remnant, when they all escape. We continue with this approximation although if shorter confinement times are allowed for higher energy particles the energy spectrum is steeper. This effect should not be important when the confinement time is much less than the pulsar and SNR age. In the case of Monogem SNR it is not completely true, but we adopt this assumption as a first approximation.

We calculate energy spectra of cosmic rays accelerated by the pulsar B0656+14 and observed now at the Earth assuming that the confinement time is the fraction of the pulsar age. The results are shown in Figure 3. It is seen that as the instant when cosmic rays are released from confinement approaches the present moment, the more highest energy cosmic rays remain within the region between the pulsar and the Earth and can be the potential source of observed gamma quanta. Comparison with Figure 1 shows the 'value' of the SNR trapping: particles above the knee (at 3 PeV) have now a higher intensity and thus this model is better able to explain the observation of particles of these high energies in practice.

## 4.5 Gamma rays from the pulsar associated with the SNR

### 4.5.1 Proton and nuclei interactions

We have calculated the expected flux of gamma quanta with energy above 1 PeV as the integral along the line of sight for gamma quanta produced in PP-collisions of protons accelerated by the pulsar with the hydrogen atoms of the ISM:

$$F(> 1\text{PeV}) = \int_0^R 2cdr \int_{1\text{PeV}}^{E_{max}^0} \frac{dN}{dE} \rho_{cr} \sigma_{in} n_\gamma(> 1\text{PeV}) \rho_{ISM} dE \quad (8)$$

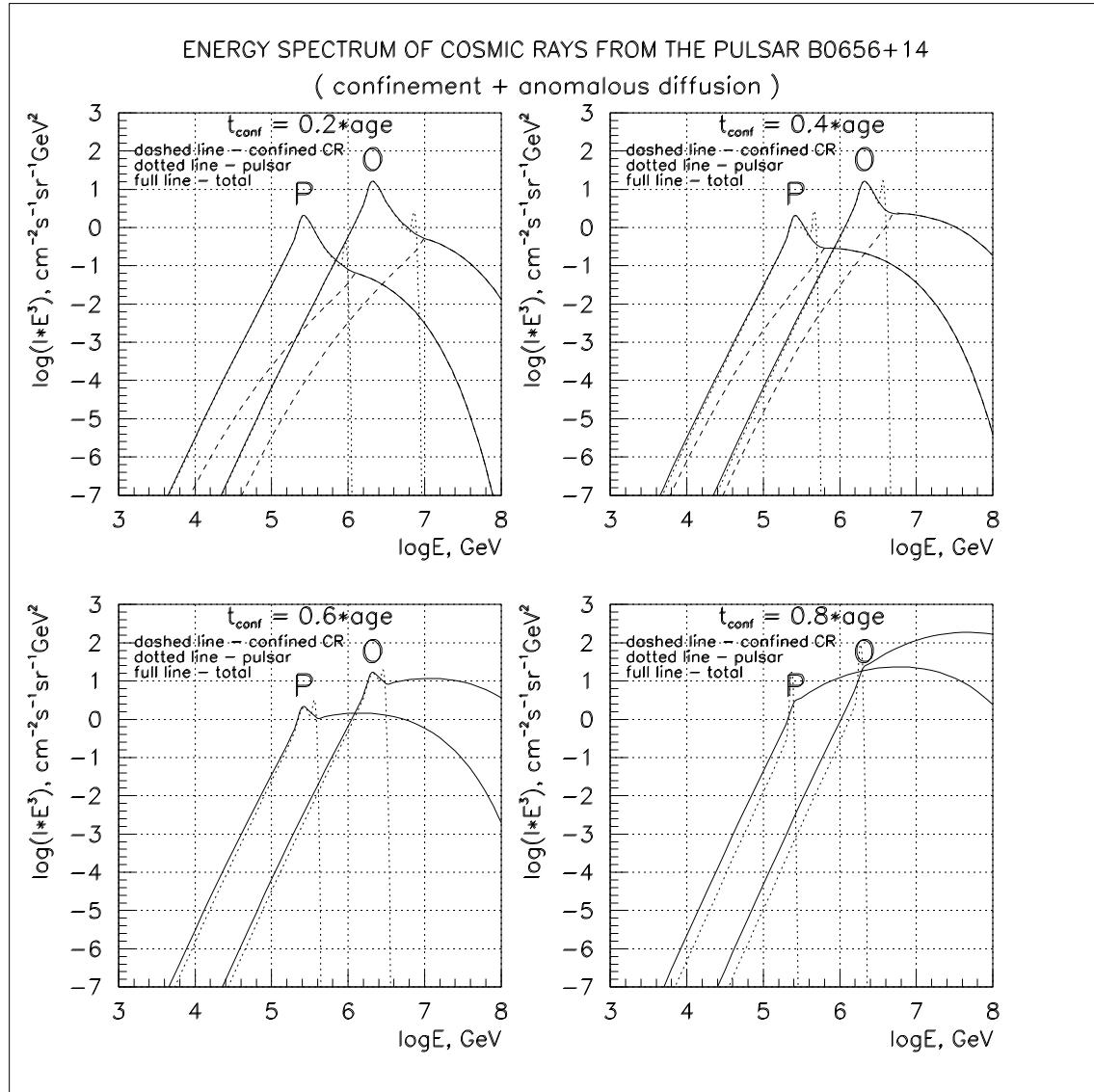


Figure 3: The energy spectrum of cosmic rays from the pulsar B0656+14 observed at the Earth, calculated for different times  $t_{conf}$ , during which cosmic rays were confined within the SNR shell and after that they were released, begin to diffuse through the ISM and escape from the Galaxy. Dashed lines indicate the contribution from the cosmic rays accumulated during the confinement time, dotted lines show the contribution from the pulsar since the end of the confinement. Full lines show the total spectrum composed of these two. The spectra are shown for the confinement time lasting (a) 0.2; (b) 0.4; (c) 0.6 and (d) 0.8 times the pulsar age.

Here  $\frac{dN}{dE}$  is the energy spectrum of cosmic rays emitted by the pulsar, confined during the time  $t_{conf} = \Delta * age$ , then released and, until the present time, survived after escape and diffusion. These spectra, and some other input parameters, are shown in Figure 4.  $\sigma_{in}$  is the inelastic cross-section of PP collisions, which has been taken as  $\sigma_{in} = 0.82 * (38.5 + 0.5 \ln^2(S/137))$ ,  $mb$  with  $S = 2M_p(2M_p + E)$  as the squared energy of PP-collision in the center of mass system,  $M_p = 0.938 GeV$  being the mass of the proton.  $n_\gamma(> 1 PeV)$  is the multiplicity of gamma quanta with energy above 1 PeV. It was calculated using the algorithm and formulae given in [30] and shown in the lower panel of Figure 4.  $\rho_{ISM}$  is the *mean* density of the target gas in the ISM, taken as  $3 \cdot 10^{-3} cm^{-3}$  since B0656+14 is situated in our Local Superbubble with its low gas density.

The term  $\rho_{cr}$  describes the lateral distribution function ( LDF ) of the cosmic ray density and is inversely proportional by the volume  $V_{cr}$  occupied by the cosmic rays. Here we follow the scenario described in [30]. The particles emitted by the pulsar were confined during the time  $t_{conf}$  within the expanding spherical SNR shell with radius  $R_s = 50\sqrt{\frac{t_{conf}}{2 \cdot 10^4 year}}$ , pc. Inside this shell they are completely isotropised and their lateral distribution is uniform. After the confinement time they are released and begin to diffuse through the ISM. As before we have taken a spherical mode of anomalous diffusion with no influence of beaming ( see (5) ), which is a reasonable assumption. The LDF of cosmic ray density was calculated as  $\rho_{cr} = \frac{1}{V_{cr}Q(E, r, t)}$  with

$$V_{cr}(E, R_s) = \frac{4}{3}\pi(R_s^3 + 3R_d^3(0.7854 + (\frac{R_s}{R_d}) \cdot 0.9986 + (\frac{R_s}{R_d})^2 \cdot 0.7849)) \quad (9)$$

where the diffusion radius was taken as  $R_d = H_z(\frac{t-t_{conf}}{\tau(E)})$  and the term  $Q = 1$  at  $r < R_s$  within the shell and  $Q = (1 + (\frac{r-R_s}{R_d})^2)^2$  at  $r > R_s$  outside the shell. Other parameters were explained before,  $R$  is taken as 288 pc. The term  $Q(E, r, t)$  determines the *shape* of the LDF and the volume (9) arises as the integral  $V_{cr} = \int_0^\infty 4\pi r^2 Q(E, r, t) dr$  which has a meaning of the effective volume occupied by cosmic rays. It has been used for the determination of the cosmic ray concentration in the central part of the SNR, i.e. at  $r < R_s$ .

Calculation of the flux for  $\Delta = 0.8$  ( dotted line in the middle panel of Figure 4 ) gives a value of  $3.7 \cdot 10^{-15} cm^{-2}s^{-1}$ , which is less than the experimental value  $\sim 10^{-13} cm^{-2}s^{-1}$  by more than an order of magnitude. However, the calculations show a strong dependence of the gamma ray flux on the value for the time when the cosmic rays were released from confinement. For instance, if  $\Delta = 0.95$  the flux rises up to  $2.0 \cdot 10^{-13} cm^{-2}s^{-1}$  and exceeds the experimental value by the factor of  $\sim 2$ . For  $\Delta = 0.99$  the flux is  $2.2 \cdot 10^{-12} cm^{-2}s^{-1}$ , which is by an order of magnitude higher than the previous value.

If the pulsar accelerates nuclei, then their energy at the fixed rigidity will be  $Z$  times higher and they are more efficient in the production of gamma-quanta [30]. However, because the total energy lost by the pulsar for the acceleration of particles is fixed, the spectrum of nuclei at the same energy is  $Z$  times lower than that of

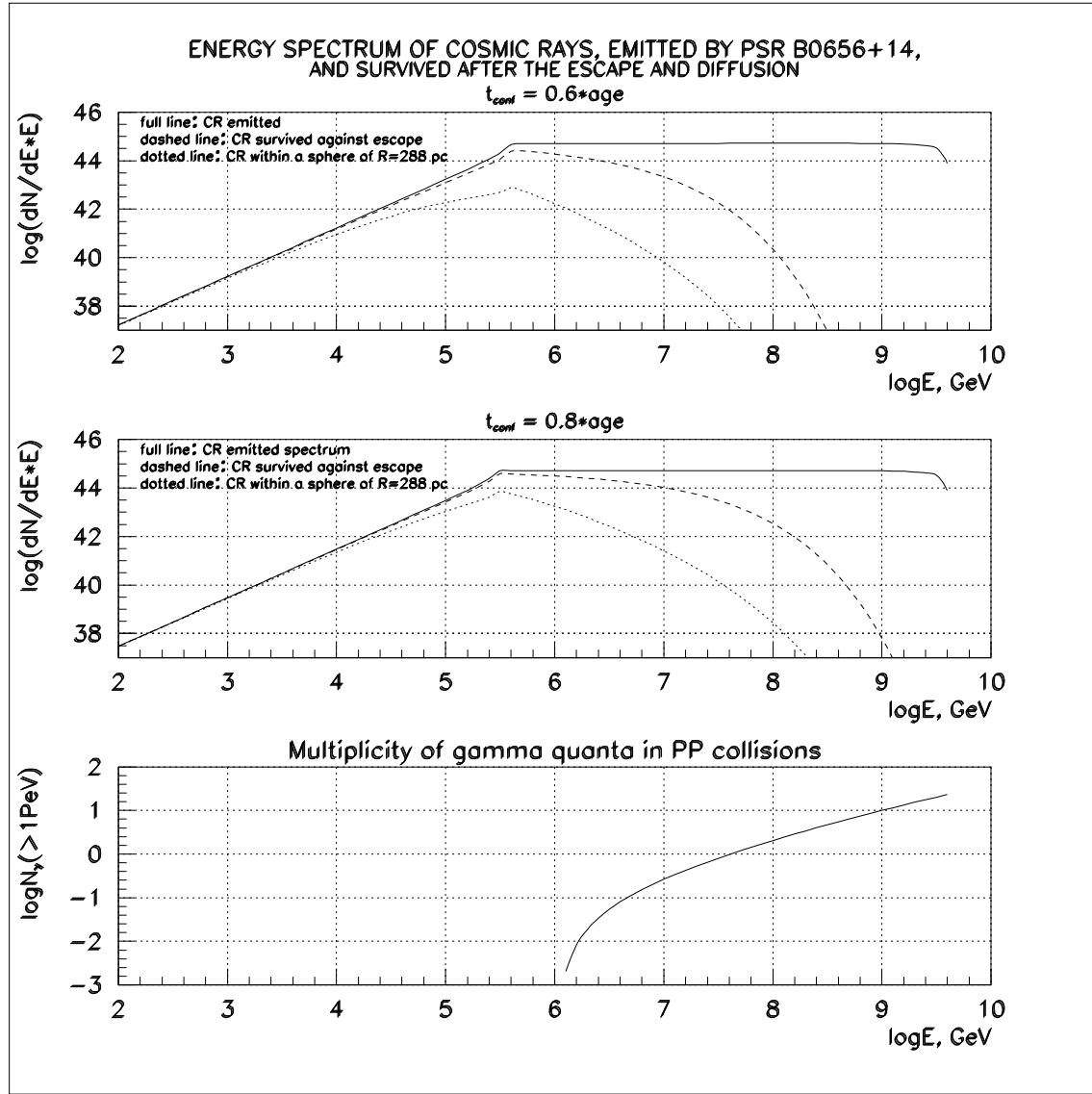


Figure 4: Energy spectrum of cosmic rays emitted by pulsar B0656+14 during its life time and survived after the escape and diffusion: upper panel - for  $\Delta = 0.6$ , middle panel - for  $\Delta = 0.8$ . Full line: the emitted spectrum, dashed line - the same spectrum surviving against escape from the Galaxy, dotted line - the spectrum of cosmic rays remaining around the pulsar within the radius  $R$  after escape and diffusion. The lower panel shows multiplicity of gamma quanta with energy above 1 PeV in PP collisions as a function of the proton energy.

protons. Since the mean production rate for gamma quanta by nuclei of the mass  $A$ , which is proportional to the product of the cross section and the number of wounded nucleons, is  $A$  times higher, then the spectra of gamma quanta from interactions of nuclei would be  $A/Z \approx 2$  times higher than that for protons.

#### 4.5.2 Electron interactions

As for mechanisms of direct production of PeV gamma rays the electromagnetic interactions of accelerated electrons can be discussed. The energy spectrum of electrons accelerated by the pulsar is similar to the rigidity spectrum of nuclei, since all the particles are accelerated by the electric field with the same potential difference.

Among the direct processes, the inverse compton scattering on microwave background photons can be excluded, since in the energy spectrum of electrons there are no energies which can boost the background photons with a mean energy of  $\sim 10^{-4}eV$  up to the PeV energies.

The mechanism which *might* be possible from the energy requirements and interaction kinematics is the inverse compton scattering of accelerated electrons on X-ray photons. The Monogem Ring is known as a source of X-rays [31, 32, 33] and inverse compton scattering of electrons on them might produce the needed PeV gamma-quanta. However, the problem with this mechanism is that electrons which are able to boost keV X-rays up to PeV energies ( $> 5 \cdot 10^8$  GeV) are produced by B0656+14 pulsar only during the first few decades. We have to confine them without substantial energy losses during  $\sim 10^5$  years up to the present time to let them scatter on X-ray photons and give the observed PeV gamma quanta. Such a long confinement time for EeV electrons without any substantial energy losses seems to be unlikely. Moreover, even if such a confinement is possible the intensity of the produced gamma quanta is by about 14 orders of magnitude less than that from PP-interactions ( 7 orders of magnitude are due to the difference in the cross sections and another 7 orders - due to the low density of X-ray photons ).

Therefore electrons could not be the source of the gamma-quanta in the Armenian peak.

#### 4.5.3 Neutrons

Neutrons being able to travel in straight lines can give rise to the narrow peak of EAS intensity from the discrete source. The processes which produce neutrons are PP-interactions with charge exchange for the projectile proton and disintegration of heavier nuclei, if they are emitted by the pulsar. The minimum energy of neutrons which can give the observed EAS with  $N_e > 10^6$  is higher than for gamma-quanta and for the Aragats altitude is equal to 2.5 PeV. We calculated the flux of neutrons from PP-interactions similarly to that of gamma quanta:

$$F_n(> 3PeV) = \int_{2.5PeV}^{E_{max}^0} dE_n \int_0^R D(E_n, r) dr \int_{2.5PeV}^{E_{max}^0} \frac{dN}{dE} \rho_{cr} \sigma_{in} n_n(E, E_n) \rho_{ISM} dE \quad (10)$$

Here most notations are the same as in (8) and  $E_n$  is the neutron energy,  $n_n(E, E_n)$  is the inclusive spectrum of neutrons produced in PP-collisions and  $D(E_n, r)$  is the survival probability of neutrons, decaying on their way from the birth place to the Earth. We have taken the inclusive spectrum of neutrons,  $n_n(E, E_n)$ , from the experimental data taken at 24 GeV [34] and assumed that they can be scaled up to PeV energies in terms of their  $x = E_n/E$  dependence. The survival probability has been taken as

$$D(E_n, r) = \exp\left(-\frac{R-r}{l_d(E_n)}\right) + \exp\left(-\frac{R+r}{l_d(E_n)}\right) \quad (11)$$

with  $l_d(E_n)$  as the decay length of neutrons.

The influence of the higher energy threshold, which leads to a smaller flux of the relevant protons and their faster diffusion from the confinement volume with a further reduction of their density, lower multiplicity of neutrons produced in PP-interactions and their decay results in a substantially lower flux of neutrons compared with that of gamma-quanta. For  $\Delta = 0.8$  the flux  $F_n(> 2.5\text{PeV}) = 4.0 \cdot 10^{-20} \text{cm}^{-2}\text{s}^{-1}$ , for  $\Delta = 0.95 - 7.4 \cdot 10^{-18} \text{cm}^{-2}\text{s}^{-1}$ .

A better opportunity is provided by heavier nuclei, if they are indeed accelerated by the pulsar. They have a higher cross-section for interaction with protons of the ISM and release multiple spectator neutrons with the same energy per nucleon without energy losses. However, the gain is not enough because of the need for energy conservation. Since the energy lost by the pulsar for the acceleration of nuclei is fixed, the number of nuclei with the same rigidity is respectively less. Moreover, to get neutrons with  $E_n > 2.5\text{PeV}$ , pulsars have to accelerate nuclei to higher rigidity than protons in order to get the same energy per nucleon. All these factors lead to fluxes of neutrons higher only by a factor less than 10. For example, if the pulsar accelerates iron nuclei and they release all their 30 neutrons after collision with ISM protons, then for  $\Delta = 0.8$ , the flux  $F_n(> 2.5\text{PeV}) = 1.2 \cdot 10^{-19} \text{cm}^{-2}\text{s}^{-1}$ , for  $\Delta = 0.95$  it is  $3.7 \cdot 10^{-17} \text{cm}^{-2}\text{s}^{-1}$ .

Therefore, neutrons, too, cannot be the particles which give rise to the Armenian peak.

## 5 Discussion

We conclude that although the pulsar B0656+14 cannot be the dominant source supplying cosmic rays in the knee region, it alone accelerates protons which can produce gamma quanta observable as an excess EAS intensity in the Armenian peak. Certainly cosmic rays from the associated SNR Monogem Ring can contribute to this intensity. The only condition is that cosmic rays from this pulsar should be confined by the associated SNR during a considerable fraction of its age.

## 5.1 Age of the pulsar and the duration of the confinement

The spin-down age of the pulsar B0656+14, determined as  $age = P/2\dot{P}$ , is equal to  $1.1 \cdot 10^5$  year. However, if indeed the higher multipoles of the magnetic fields [27, 28] or gravitational radiation [14] are important, the actual energy losses at the initial period of the pulsar evolution can be higher and its observed rotation parameters could be reached in a shorter time, leading to a smaller age. The model age is estimated as  $8.6 \cdot 10^4$  year [33]. If we use this shorter age the estimated flux of gamma quanta for  $\Delta = 0.95$  rises up to  $2.9 \cdot 10^{-13} cm^{-2}s^{-1}$ , leaving a safe gap of  $< 40\%$  efficiency for the conversion of the pulsar energy into cosmic rays. The fraction of  $\sim 95\%$  of the age, required for the confinement time means that the cosmic rays were trapped inside the SNR for about 82 kyear. Remarkably, this value coincides with the 80 kyear adopted by our model of the SN explosion and acceleration of cosmic rays [4]. It means that cosmic rays had only a few kyears to diffuse and that is why only high energy particles reached the Earth forming the sharp knee.

## 5.2 The contribution of B0656+14 beyond the knee

If the age is fixed and the confinement time increases, less time remains for diffusion and escape. The observed spectrum of cosmic rays then approaches the emitted spectrum. Since the emitted spectrum is as flat as  $E^{-1}$  [14, 15, 16] then if the fraction  $\Delta$  approaches 0.9, then the intensity of cosmic rays from the pulsar B0656+14 calculated in §4.4 exceeds the observed values at high energies beyond the knee. In principle it might create problems for our explanation of the origin of the Armenian peak. However, we remember that calculations were made for 100% efficiency of the conversion of the pulsar rotation energy into cosmic rays and for a *mean* ISM density  $\rho_{ISM} = 3 \cdot 10^{-3} cm^{-3}$ . Since we assume that the Armenian peak is due to interactions of cosmic rays with the local perturbation of the ISM density we can safely reduce the efficiency of conversion not to exceed the observed cosmic ray intensity and increase the local ISM density respectively to preserve the same flux of gamma-quanta as observed in the peak.

Our estimate of the flux has been made as the integral along the line of sight through the whole SNR. However, the size of the bin for the Armenian peak is  $\sim 10$  times smaller than the size of the SNR. In order to get the same grammage, for which we obtained the flux comparable with observed, we have to increase the gas density in the local perturbation by the factor of  $\sim 10$  up to  $\sim 3 \cdot 10^{-2} cm^{-3}$ . Since the mean gas density in the Galaxy is  $\sim 1 cm^{-3}$  such an increase seems possible.

We should also remark that the contribution of the pulsar B0656+14 to cosmic rays beyond the knee might be considerable and grow with energy up to  $10^8$  GeV. If it is true, and taking into account that the mass composition of cosmic rays beyond the knee becomes heavier with a growing amount of iron [35, 36], we have to conclude that the pulsar B0656+14 can emit iron nuclei.

### 5.3 The connection between the pulsar and the SNR

The confinement of high energy cosmic rays by the SNR raises other interesting problems: how can the Monogem Ring SNR, which according to our model accelerates cosmic rays only up to 0.4 PV, rigidity trap and confine for a long time particles with rigidities up to  $10^3$  PV ? A possible idea for such a scenario is that SNR with their large sizes and moderate magnetic fields are efficient in the acceleration of relatively large fluxes of particles up to moderate sub-PeV and PeV energies, whereas a pulsar which has much higher magnetic fields in a much smaller volume, can accelerate smaller fluxes of particles reduced further by beaming, but up to much higher super-PeV energies. It means again that the pulsar B0656+14 and, probably, other pulsars, might be serious contenders for the sources of cosmic ray particles beyond the knee, discussed often as the so called ‘second component’ of cosmic rays in two- or three-component models ( eg. [37, 38, 39, 40, 41]).

### 5.4 Position of the Armenian peak and the pulsar B0656+14

There is a potential difficulty in the association of the Armenian peak with the pulsar. It is the mutual position of the region where the EAS intensity peak is observed , the pulsar position and the direction of its proper motion. Chilingarian et al. remark that despite the fact that their intensity peak is inside the Monogem Ring SNR it is displaced from the pulsar position by  $8.5^\circ$  ( Figure 5 ). It is rather far. Moreover, if the excess EAS intensity is due to the interaction of cosmic rays produced by the pulsar in the past, then the direction of its proper motion should be away from the region where it was in the past. On the contrary, the direction of B0656+14’s proper motion is towards the region of the peak.

It must be remarked that there may be a problem with the absolute celestial alignment of the MAKET-ANI array [24] and this problem may go away.

However, even if everything is correct, our scenario with a long confinement could give an explanation for the possible misalignment of the pulsar and the Armenian peak. The diffusion radius of PeV protons reached in 4 kyears is 100 pc and a sphere of this radius can be seen from a distance of 300 pc at an angle of about  $20^\circ$ . It means that PeV cosmic rays have overcome the parent pulsar and its proper motion is not necessarily connected with the regions of the highest cosmic ray density. Within the sphere the density of cosmic rays is presumably uniform and any kind of local ISM density perturbation or a local molecular cloud could create the excess intensity of gamma quanta. In this connection it would be interesting to search for other possible excesses in this area.

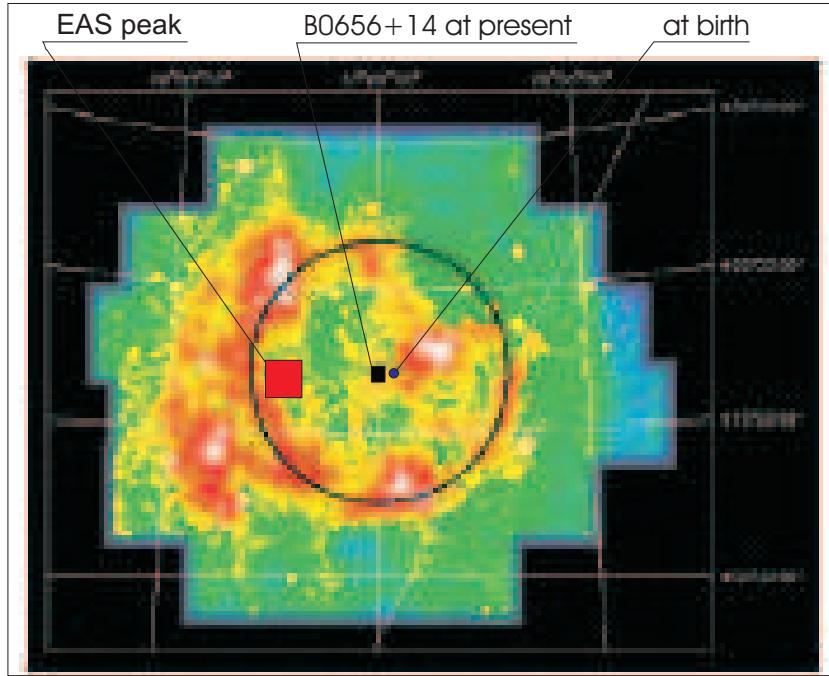


Figure 5: The Monogem Ring, as seen in the ROSAT all-sky survey in the 0.25-0.75 keV X-ray band. PSR is at the center of the Figure and the circle is of the radius  $9.2^\circ$  centered on this point. The circle indicates the primary ring structure. The position of the pulsar  $10^5$  years ago, estimated from its proper motion, is marked with a small square about  $1^\circ$  to the right of its present position ( this figure was copied from [12] ). The angular bin where Chilingarian et al. have found an excessive intensity of EAS is shown by the big square, marked 'EAS peak'

## 5.5 The search for other EAS intensity excesses in MAKET-ANI data

The results from the experiment of Chilingarian et al. [3] are so potentially important that further analysis is clearly worthwhile. The question to be asked is: irrespective of the likely association of the main peak with the pulsar in the Monogem Ring, is the rest of the data consistent with there being a whole family of sources in the PeV region ? This possibility is not fanciful: there is the well-known presence of ‘unidentified’ GeV sources and at least one TeV peak [42] does not ( yet ) appear to have been identified.

In terms of pulsars of age less than  $10^5$  y we expect  $\sim 1000$  in the Galaxy at the present time (  $10^{-2} y^{-1}$  birth rate ). The MAKET-ANI array covers about 30% of the sky and about 50% of the Galactic Plane region (  $|b| \simeq 20^\circ$  ). Thus  $\sim 500$  sources might be present. Using the analysis already described, those within  $\sim 0.5$  kpc might be directly discernible, viz  $(0.5/15)^2 \times 500, \simeq 0.5$ . The potential Monogem source falls in this category. The question is the presence, or otherwise, of weaker sources and their contribution to the overall flux.

Inspection of Figure 6(a), taken from [3], which relates to distribution of significances for the whole sky seen by the array, shows evidence for an excess of about 11 ‘events’ beyond  $\sigma \sim 2$ . The corresponding fluxes are  $>1/9$  times the Armenian peak flux. If all the events were along the Galactic Plane we would have expected of order  $0.5 \times 9$  i.e.  $\simeq 5$ . In fact, the Galactic latitudes of the events in Figure 6(a) are not known but it is evident that a good case can be made for some extra, weak sources. Indeed, if, following our arguments [28] for spun up pulsars, at high Galactic latitudes, being responsible for some of the very energetic particles, we could imagine a wider distribution in Galactic latitude. The expected number would be correspondingly greater ( for 3-D compared with 2-D, the number would go up by  $9^{\frac{3}{2}} = 27$  cf 9 ).

Figure 6(a) is reminiscent of the result from the Tibet-III Air Shower Array [44]. In a similar significance plot, upward deviation occur increasingly above  $3\sigma$ , reaching a factor 2 above  $4\sigma$ .

Figure 6(b) is our own plot of the array data in terms of deviation from the mean for the restricted declination range (  $\delta : 12.5^\circ - 15.5^\circ$  ) which crosses Monogem. Again, we see evidence for a small excess of positive excursions from the mean for positive values. Examining the basic data for this  $\delta$ -range, we find no evidence for an excess, of large fluxes near the Galactic Plane, however. Again, the sources may be more widely distribute than just in the Galactic Plane.

## 5.6 Possible contribution of other pulsars to the knee

It is well known that some pulsars emit energetic gamma rays ( see [45] for a review ). If we regard the early ‘observation’ of Cygnus X-3 [46, 47] as showing that pulsars *do* emit PeV gamma rays, albeit spasmodically, then a way forward appears. Cyg X-3 appears to have given a flux above 1 PeV of  $\approx 3 \cdot 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$  when ‘on’; its distance is 11.4 kpc, so that fluxes of order  $4 \cdot 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$  would be expected for sources at  $\sim 300$  pc. There would therefore be no problem of flux for B0656+14, with its measured flux of  $10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$ . Even the many upper limits from other workers who have searched for Cygnus X-3, and which are typically a factor 100 below the ‘observations’, would not be inconsistent with the Armenian peak expectation.

Bhadra examined the possibility for pulsars to form the knee and concluded that Geminga and Vela are the most likely candidates [13]. We calculated energy spectra of cosmic rays produced by these pulsars, considering them as isolated pulsars; they are shown in Figure 7.

Since Geminga is older than B0656+14 ( its age is  $3 \cdot 10^5$  y ), its maximum rigidity will be 0.19 PV, therefore it could contribute to the knee energies only if it accelerates iron nuclei. In this case there is no room for the ‘second knee’ in the interval 10-20 PeV found by us and included in the Single Source Model as an ‘iron peak’.

Vela is much younger (  $\sim 10^4$  year ). Its maximum rigidity is right in the knee region of  $\sim 2.8$  PV, so that it could contribute even by accelerating protons. The

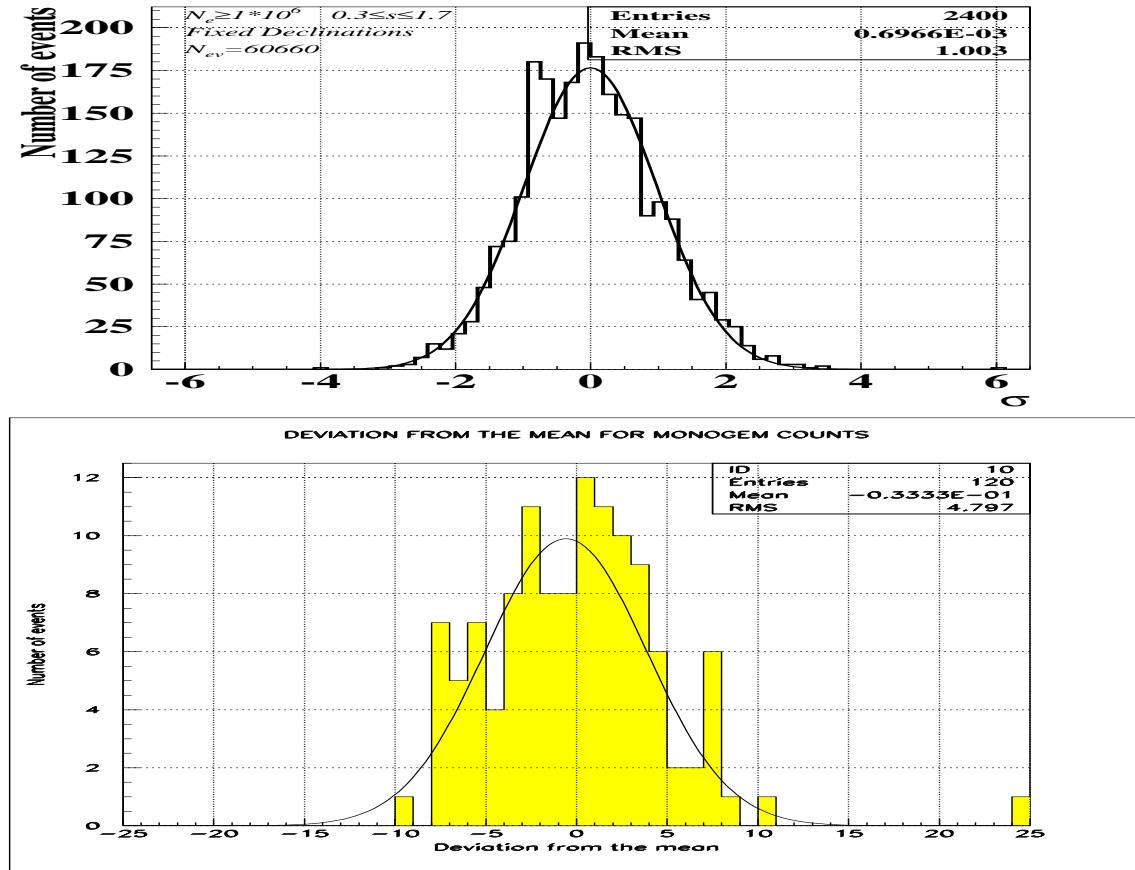


Figure 6: (a) Signal significance test with full equatorial coverage with  $2400 3^\circ \times 3^\circ$  bins;  $N_e > 10^6$ . (b) Frequency distribution of deviations from the mean in the number of events per  $3^\circ$ RA bin in the cut along  $\delta : 12.5^\circ - 15.5^\circ$ . The data relate to the EAS observations of Chilingarian et al. [3]

intensity can be adjusted by introducing the efficiency of conversion of the pulsar rotation energy to the accelerated particles at the level of 10%, which is a reasonable value. However, the Vela pulsar is associated with a young SNR and most likely its accelerated cosmic rays are still confined in the SNR shell.

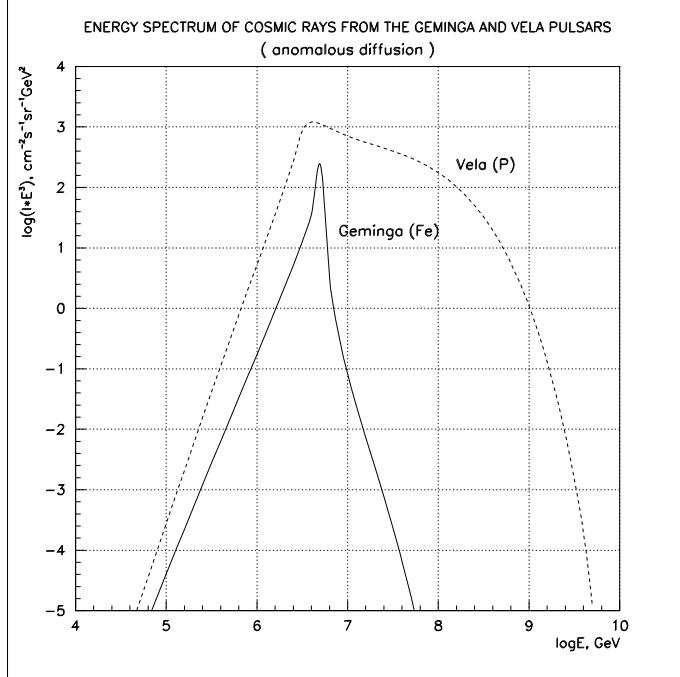


Figure 7: Energy spectra of cosmic rays produced by the Geminga and Vela pulsars. Full line: Geminga, accelerating iron nuclei, dashed line: Vela, accelerating protons.

## 5.7 Predictions

The scenario described here let us make three predictions for the Monogem Ring results, which could be checked experimentally:

- (i) since the only mechanism responsible for the formation of the EAS intensity peak appears to be gamma ray production in PP-collisions, the excess showers in the peak should have different characteristics from the background showers. They should have features typical of electromagnetic cascades ;
- (ii) even if the peak is created by the pulsar, the fact that cosmic rays responsible for it were produced in the past, were confined and most likely mixed with cosmic rays from the SNR, the gamma ray emission should not be pulsed ;
- (iii) due to the non-uniform character of the ISM there might be some other excesses in the Monogem Ring area due to other local perturbations of the ISM density, most likely of smaller amplitude.

## 6 Conclusions

We conclude that the pulsar B0656+14 can contribute to the intensity of cosmic rays in the knee region, but cannot be the dominant source responsible for its formation. Its contribution to the intensity of the Single Source, needed to form the sharp knee, appears not to exceed 15%. The SNR associated with the Monogem Ring, rather than the pulsar, still remains the most likely Single Source which gives the dominant contribution to the formation of the cosmic ray energy spectrum in the vicinity of the knee.

We have also examined the possibility of the pulsar B0656+14 giving the peak ( the 'Armenian peak' ) of the EAS intensity, observed from the region inside the Monogem Ring. The estimates of the gamma-ray flux produced by cosmic ray protons from this pulsar evidence that it can be the source of the observed peak, if the protons were confined within the SNR during a considerable fraction (  $\sim 90\%$  ) of its total age. The flux of gamma quanta at PeV energies has a high sensitivity to the duration of the confinement. The estimate of this time and the following diffusion of cosmic rays from the confinement volume turns out to be in remarkable agreement with the time needed for these cosmic rays to propagate to the solar system and to form the observed knee in the cosmic ray energy spectrum.

Other possible mechanisms for the production of particles which could give rise to the Armenian peak were also examined. Electrons scattered on the microwave background or on X-rays, emitted by SNR, could not be responsible for the gamma-quanta in the peak. Neutrons produced in PP - collisions or released from the spallation of accelerated nuclei also seem to be improbable mechanisms since they cannot give the observed flux.

If the EAS results are confirmed, they will be important, since

- (i) they give evidence for the possibility of the acceleration of protons by the pulsar;
- (ii) they give evidence for the existence of a confinement mechanism in SNR ;
- (iii) they confirm that cosmic rays produced by the Monogem Ring SNR and associated pulsar B0656+14 were released recently giving rise to the formation of the sharp knee and the observed narrow peak in the EAS intensity ;
- (iv) they give strong support for the Monogem Ring being identified as the source proposed in our Single Source Model of the knee.

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